Motion Control	Console Position: ADCO
Angular Velocity, Angular Momentum, Moment of Inertia, Acceleration and Torque	

Control Moment Gyroscopes

What Keeps the International Space Station (ISS) from Tumbling Through Space?

Instructional Objectives

Students will

- discuss the fundamental function of a gyroscope and how control moment gyroscopes (CMGs) work in three-dimensional (3D) space to orient the ISS;
- convert wheel speed in revolutions per minute (rpm) to radians per second;
- calculate the moment of inertia of a CMG;
- determine the radius of a CMG based on the angular momentum;
- calculate the kinetic energy of a CMG;
- calculate the linear velocity of the outer edge of a CMG; and
- determine magnitude of the resultant torque generated by CMGs in 3D.

Degree of Difficulty

This problem requires students to integrate several aspects of the AP* Physics curriculum to obtain the solution. For the average AP Physics student, the problem may be moderately difficult.

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Total Time Required

Teacher Prep Time: 5–10 minutes

Class Time: 60–80 minutes

(To decrease amount of class time, students may complete research as homework via the Internet using the ISSLive! website or mobile application.)

- Introduction: 5–10 minutes
- Student Research: 20–25 minutes
- Student Work Time: 25–30 minutes
- Post Conclusion: 10–15 minutes

Lesson Development

This problem is part of a series of problems associated with the NASA International Space Station *Live!* (ISS*Live!*) website at http://spacestationlive.nasa.gov.

Teacher Preparation

- Review the Motion Control System information on the ISS*Live!* website. This information is found at the *Operations* tab, under *Core Systems*.
- Review the Attitude Determination and Control Officer (ADCO) Handbook, paying specific attention to the control moment gyroscopes (CMGs). This handbook is found at the ADCO console position in the 3D Mission Control Center environment (under the *Interact* tab, then *Explore Mission Control*).
- Review the ADCO console display in the 3D Mission Control Center environment and the live data associated with the CMG. The displays may be accessed by *clicking on the console screens*.

ADCO Console Display

- Review the interactive activity at the ADCO console position in the 3D Mission Control Center environment by *clicking on the bat and ball* on top of the console. This activity demonstrates how CMGs work to maintain the attitude of the ISS.
- Prepare copies of the STUDENT WORKSHEET (Appendix B).

Inquiry-Based Lesson (Suggested Approach)

1. Pose this question to the class:

    The International Space Station (ISS) orbits the Earth every 90 minutes. During its orbit, it maintains the same side of the vehicle (facing the Earth). How does the ISS maintain this orientation, or attitude, throughout its orbit?

2. Allow students to discuss the question in small groups or as a class. Have students create their own questions and possible solutions to the problem.
3. Distribute the STUDENT WORKSHEET (Appendix B) to the students.
4. Students may work individually or in small groups (2–3 members per group) to conduct the research. Students should access the ISS*Live!* website and explore the 3D Mission Control Center. If needed, guide students to the Attitude Determination and Control Officer (ADCO) console position. They should access the ADCO Handbook and ADCO console displays, as well as the interactive activity, as they prepare to answer the questions on the STUDENT WORKSHEET. This research may be assigned as homework.
5. Once the research is completed, students may work individually to complete the questions on the STUDENT WORKSHEET. They should refer to the live data on the ADCO console displays located on the ISS*Live!* website to answer the entire problem.

Post Conclusion

6. A SOLUTION KEY (Appendix A) is provided below using data that is typical for normal operations of the CMG. Students' answers will vary depending on the actual live data.
7. Have students discuss their answers in small groups or with the entire class and tie back to the original question:

    The International Space Station (ISS) orbits the Earth every 90 minutes. During its orbit, it maintains the same side of the vehicle (facing the Earth). How does the ISS maintain this orientation, or attitude, throughout its orbit?

8. Ask students to explain the Control Moment Gyroscopes (CMG)and the data they used in their calculations.
9. Assessment of student work may be conducted by using the provided rubric (modeled after AP Free Response Question scoring).

Extension

Other possible uses for the ISS*Live!* website, focusing on ADCO and Motion Control System:

- Based on the students' answers from question 7 students can use a torque wrench to experience the amount of torque being exerted by CMGs on the ISS. Remind the students of the size and mass of the ISS. (Mass data can be found on the ISS*Live*! website under the ADCO console.)

- Revisit the ADCO console position to check the CMG live data at different points in its orbit, or during special activities such as space walks, reboosts, etc. (Check the timeline for activities, located under *Live Data*.)

AP Course Topics

Circular Motion and Rotation

- Uniform circular motion
- Torque
- Rotational kinematics and dynamics
- Angular moment and its conservation

NSES Science Standards

Science as Inquiry

- Abilities necessary to do scientific inquiry
- Understanding about scientific inquiry

Science in Personal and Social Perspectives

- Science and technology in local, national and global challenges

Physical Science

- Conservation of energy and increase in disorder

Science and Technology

- Abilities of technological design
- Understanding about science and technology

History and Nature of Science

- Science as a human endeavor
- Nature of scientific knowledge

Contributors

This problem is part of a series of problems developed by the ISS*Live!* Team with the help of NASA subject matter experts.

Education Specialist

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NASA Experts

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Scoring Guide

Suggested 10 points total to be given.

Question		Distribution of points
1	*1 point*	1 point for recognizing the change in momentum vectors and generation of torque
2	*1 point*	1 point for identifying the change in orientation (attitude)
3	*2 points*	1 point for correct calculation of angular velocity with the correct units 1 point for correct calculation of moment of inertia using $L = I \cdot \omega$
4	*1 point*	1 point for calculating the correct radius of the CMG
5	*1 point*	1 point for the correct quantity of kinetic energy
6	*1 point*	1 point for the correct linear velocity with the correct units
7	*2 points*	1 point for identifying the sum of the square of the torques 1 point for correct calculation of resultant magnitude of torque
8	*1 point*	1 point for identifying a gyroscope in a device and contrasting and comparing it to the CMGs on the ISS

APPENDIX A

SOLUTION KEY

CONTROL MOMENT GYROSCOPES

What Keeps the International Space Station (ISS) from Tumbling through Space?

The Motion Control System is primarily monitored and controlled by the Attitude Determination and Control Officer (ADCO) flight controller. The ADCO flight controller works in the Mission Control Center (MCC) for the International Space Station (ISS), along with a team of other flight controllers. One function of the Motion Control System is to manage the orientation, or attitude, of the ISS. The ADCO flight controllers monitor this data for safe operations of the ISS in its orbit. To learn more, explore the 3D ISS Mission Control Center by accessing *Explore Mission Control* under the *Interact* tab on the ISS*Live!* website at http://spacestationlive.nasa.gov.

Student Research

- Review the Motion Control System information on the ISS*Live!* website. This information is found at the *Operations* tab, under *Core Systems*.
- Review the Attitude Determination and Control Officer (ADCO) Handbook, paying specific attention to the control moment gyroscopes (CMGs). This handbook is found at the ADCO console position in the 3D Mission Control Center environment (under the *Interact* tab, then *Explore Mission Control*).
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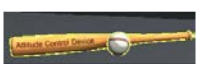

- Review the interactive activity at the ADCO console position in the 3D Mission Control Center environment by *clicking on the bat and ball* on top of the console. This activity demonstrates how CMGs are used to maintain the proper attitude for the ISS.

Student Assignment

The orientation, or attitude, of the International Space Station (ISS) is set so that a particular side of the ISS is facing the Earth throughout the entire orbit. Attitude is controlled either by firing a set of rocket engines or by managing momentum with control moment gyroscopes (CMGs). Since firing rocket engines consumes propellant and requires resupply, CMGs are the preferred method of controlling the attitude of the ISS.

There are four CMGs mounted on the truss of the ISS, and they are powered by electricity supplied by the solar arrays. To maintain the desired attitude of the ISS, the orientation of the CMGs is adjusted to counteract a potential change in attitude which could be caused by a disturbance torque.

Visit the ADCO console display in the 3D Mission Control Center environment and view the control moment gyroscope data to answer the following questions.

1. The control moment gyroscopes (CMGs) on the ISS are mounted in a two-degree-of-freedom gimbal system (with two gimbals per rotor) that can point the spin axis of the wheel in any direction. Discuss what is affected by changing the angle of the CMG gimbals.

    By changing the gimbal angles, the direction of the wheel's momentum vector changes, therefore causing a torque to be generated on the vehicle.

2. Discuss how changing the gimbal angles on the CMG would affect the ISS.

    As discussed in question 1, by changing the gimbal angles, the direction of the wheel's momentum vector changes. This change exerts a torque on the ISS, therefore causing a shift in the attitude.

3. The Motion Control System, and its ability to control the attitude of the ISS, is complex. In order to understand the system as a whole, an examination of CMGs is important. Determine the moment of inertia of one CMG by using live data from the ISS*Live!* website on the revolutions per minutes (rpm) of a CMG and by determining its angular velocity.

    a. What are the current revolutions per minute (rpm) of one CMG?

        Based on the ADCO console display, assume a value of 6,601 rpm for CMG 2.

    b. Use the live data from part a. (above) to determine the CMG's angular velocity, ω.

$$\frac{6601\,\text{revolutions}}{1\,\text{min}} \cdot \frac{1\,\text{min}}{60\,\text{sec}} \cdot \frac{2\pi\,\text{rad}}{1\,\text{revolution}} = 691.3\,\frac{\text{rad}}{\text{sec}}$$

    c. Each CMG rotates roughly at a constant speed and develops an angular momentum of 4,880 Newton meters seconds (N·m·s) about its spin axis. Calculate the CMG's moment of inertia.

$$L = I \cdot \omega$$

$$4880\,\frac{\text{kg}\cdot\text{m}^2}{\text{sec}} = I \cdot 6912\,\frac{\text{rad}}{\text{sec}}$$

$$I = \frac{\dfrac{4880\,\text{kg}\cdot\text{m}^2}{\text{sec}}}{691.2\,\dfrac{\text{rad}}{\text{sec}}} = 7.060\,\text{kg}\cdot\text{m}^2$$

4. Each CMG consists of a large, solid, flat stainless steel flywheel that has a mass of approximately 99.8 kilograms (kg). Calculate the radius of the wheel.

$$I = 1/2 \cdot m \cdot r^2$$

$$7.060\,\text{kg}\cdot\text{m}^2 = 0.5 \cdot 99.8\,\text{kg} \cdot r^2$$

$$r = \sqrt{\frac{7.060\,\text{kg}\cdot\text{m}^2}{0.5\cdot 99.8\ \text{kg}}} = 0.376\,\text{m}$$

5. Determine the quantity of kinetic energy contained by the CMG when it is spinning.

$$K = \frac{1}{2}\cdot I\cdot\omega^2$$

$$K = \frac{1}{2}\cdot 7.060\,\text{kg}\cdot\text{m}^2\left(691.3\,\frac{\text{rad}}{\text{sec}}\right)^2$$

$$K = \frac{1.686\text{kg}\ \cdot\text{m}^2}{\text{sec}^2}$$

or

$$K = 1.686\,x\,10^6\ \text{J}$$

6. Calculate the linear velocity on the outer edge of the CMG due to its rotational speed.

$$v = r\cdot\omega$$

$$v = 691.2\,\frac{\text{rad}}{\text{sec}}\cdot 0.376\,\text{m}$$

$$v = 259.9\,\frac{\text{m}}{\text{sec}}$$

7. The CMG torque values on the ISS*Live!* website show the combined torque of all four CMGs onboard the ISS. They are broken down into the roll, pitch, and yaw axes. Use the three component values to calculate the single resultant magnitude of torque of the ISS in Newton meters (N·m).

$$\tau_{ISS} = \sqrt{\tau_{yaw}{}^2 + \tau_{pitch}{}^2 + \tau_{roll}{}^2}$$

$$\tau_{ISS} = \sqrt{0.35^2 + 3.33^2 + -1.27^2}$$

$$\tau_{ISS} = \sqrt{12.8243}$$

$$\tau_{ISS} = 3.6\ \text{N}\cdot\text{m}$$

8. Gyroscopes are used in many devices, some which you may use on a daily basis. Identify one such device and compare and contrast the purpose of the gyroscope on that device with the CMGs onboard the ISS.

Answer will vary and can include video game controllers, cell phones and other devices.

The gyroscopes in game controllers and cell phones are tiny Microelectromechanical systems (MEMS) gyroscopes that use a vibrating structure instead of a rotating wheel as is used in the CMGs. Also, the MEMS gyroscopes in game controllers and cell phones measure the orientation of the object, whereas the ISS Control Moment Gryoscopes control the ISS orientation.

References:
http://mobilegyros.blogspot.com/
http://www.sensorsmag.com/sensors/acceleration-vibration/an-overview-mems-inertial-sensing-technology-970
http://www.invensense.com/mems/gyro/documents/whitepapers/MEMSGyroComp.pdf

One use of gyroscopes very similar to the ISS CMGs is to prevent a boat or yacht from rolling side to side in waves. A wheel weighing several hundred pounds and spinning very fast (to create momentum) is mounted as a gyroscope on the boat. Waves create torques on a boat, causing the boat to roll side to side. A computer controls the motion of the gyroscope wheel (and therefore changes the momentum direction) to create opposite torques and prevent the boat from rolling.

References:
http://www.antirollinggyro.com/CMS/00015.html
http://www.youtube.com/watch?v=qHBeD5zBZLk
http://www.youtube.com/watch?v=DRDhS_aM1v4
http://www.seakeeper.com/downloads_latestvideo.php
http://www.shipdynamics.com/index.php/gyroscopes

APPENDIX B

STUDENT WORKSHEET

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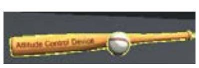

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